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DELINEATING CULTURAL MODELS

Shane T. Mueller

Applied Research Associates, Inc.
1750 Commerce Center Boulevard, North
Fairborn OH 45324-6362

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AIR FORCE MATERIEL COMMAND
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MICHAEL J. YOUNG
Work Unit Manager
Behavior Modeling Branch

DAVID G. HAGSTROM
Anticipate & Influence Behavior Division
Human Effectiveness Directorate
711th Human Performance Wing
Air Force Research Laboratory

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14. ABSTRACT
This research describes research conducted in order to develop an understanding of the cognitive factors that influence cultural models of belief. We evaluated the current state of the art in opinion dynamics research, and provided a brief review of the main issues connecting memory representation and representation in opinion dynamics. We also identified an extended bibliography covering representations and functions in cultural modeling research, and a database of news headlines highlighting potential real-world sources of cultural beliefs in conflict. Finally, we present two research articles that describe a new simulation approach to opinion dynamics that use belief spaces rather than simple single-value attitudes to represent the knowledge being exchanged.

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SUMMARY

This report describes the results of one phase of a research effort aimed at delineating the representations, constraints, and other aspects of cultural models. The report includes a basic description of the research effort, an in-depth review regarding research on opinion dynamics, a bibliography of collected research on cultural and belief modeling, a set of new article headlines illustrating situations where cultural beliefs appear to be in conflict, and two papers describing simulation work conducted under this effort.

1.0 INTRODUCTION

Cultural beliefs and behaviors have been studied with a variety of methods. We performed this research effort to understand the breadth of representations of cultural models, and to identify ways in which cognitive theory could help improve and constrain social models of belief exchange. In service of this effort, we engaged in a substantial literature review in which we examined how cultural representations have been used across domains, including anthropology, social psychology, cognitive science, computer science, economics, human factors, psychology, and other related domains. This work produced several outcomes, including the review of opinion dynamics literature found in the main section of the report, two papers concerning simulation models of belief dynamics, a comprehensive bibliography covering cultural representations issues in a number of domains, and a database of current news stories that illustrate cultural beliefs in conflict.

2.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The work conducted under the scope of this contract involved two broad research thrusts. First, we conducted a broad survey of the literature on cultural models, belief transmission, and the typical representations used in cultural belief research. This review covered representative work in anthropology, psychology, modeling, simulation, statistical analysis, sociology, and other cultural domains. One area of this literature review explored, in detail, is research on opinion dynamics and cultural transmission. Section 2 provides a broader summary of this research and Appendix A has a detailed categorized bibliography. Over the course of the year, we also collected occasional news articles that illustrated cultural beliefs in conflict. We archived full text of these news articles for possible future analysis; however, in this report we simply include a bibliography of their headlines (Appendix D).

A second major thread of this research effort built on the literature review and detailed analysis of opinion dynamics research. It involved developing simple simulation models that used complex knowledge representations to explore the way in which cognitively genuine knowledge can improve our understanding of opinion dynamics. The simulation models produced two major results: 1) it demonstrated that the bounded influence conjecture, which appears as a prominent assumption in many simulation models of opinion dynamics, is not necessary to produce competing belief factions and avoid collapse to a single belief consensus. Instead, the simulation models we developed showed that encouraging agents to adopt belief systems that are non-contradictory and self-consistent could create competing factions. That is, if an agent is unwilling to hold two beliefs that are logically, traditionally, or theologically inconsistent, this can prevent smooth movement to the center via continuous interaction with other agents having differing opinions. 2) These assumptions produce a novel account of the group polarization phenomenon: the finding in social group processes research that the average belief of a group of individuals tends to become extreme when they discuss, interact, and attempt to create a consensus. The model's account is that extreme views are easier to come to an agreement about because they tend to be the closest to the constellation of moderate views the group started with. Two papers included in this report describe this research thread. First, a conference paper accepted to a workshop on cognitive underpinning of social science, held at the Cognitive Science conference (Appendix B). We have expended this research and extended it in the form of an in-progress manuscript submitted for publication. The current manuscript is in Appendix C.

Overall, the research conducted under this project has focused on trying to understand how cognitive processes and knowledge representations can inform cultural modeling. We believe that it offers substantial promise. First, by making more nuanced assumptions about knowledge representation, we find it possible to avoid ad hoc assumptions about interaction rules. Second, by allowing more-complex representations, the research has a better chance of making contact with empirical research, so that specific cultural knowledge collected across cultural groups and nationalities can directly form part of the knowledge space of a simulation model.

3.0 RESULTS AND DISCUSSION

One community of practice engaged in developing models of cultural knowledge is referred as *Opinion Dynamic* (see Lorenz, 2007, for a survey of the field). Lorenz states that interests in this field range:

from emergence of fads, minority opinion spreading, collective decision making, finding and not finding of consensus, emergence of political parties, minority opinion survival, emergence of extremism and so on (pg. 1).

These models typically involve representing a population of agents, each of whom holds an "opinion," typically represented by a number. A variety of modeling frameworks and concepts exist, but most are concerned about how the opinions of a population of interacting agents changes with time. Hegselmann and Krause (2002) cite the work of DeGroot (1974), Lehrer (1975), and French (1956) as seminal exemplars of "classical" opinion dynamics.

As with any population model, it is important to distinguish between an average belief and an individual belief. Critically, for some systems of knowledge representation, an individual can never hold the average belief of a group of agents, for other systems, it can. This ties directly to the type of representation used in the model, and has consequences for the types of knowledge the model is best able to capture.

3.1 Representations Used in Opinion Dynamics Models

The evolution of representations used in the opinion dynamics domain appears to be driven by intuitions about knowledge transfer rather than by attempts to capture one type of knowledge vs. another. Table 1 catalogues a basic summary of several classes of representations. Perhaps the simplest way to view an opinion is as a single observation of whether one does or does not support an issue or belief. Opinion takes on one of two values, which, for example, could be mapped to the set $\{0, 1\}$, or possibly $\{-1, 1\}$, indicating opposing vs. favoring. Such a representation is appealing from an empirical perspective because it is similar to a vote, where one must determine whether one does or does not support a specific option. It has also been noted that it is appealing because models arising from Physics such as the Ising Spin model of ferromagnetism have well-understood properties that capture such two-state representations.

Table 1: Summary of Representations used in Different Cultural Models, and Related Cognitive Models Using Similar Representations

	Binary Opinions	Multi-level Discrete	Multi-dimensional	Continuous Opinions: Bounded Confidence	Continuous Opinions: Relative Agreement	Continuous Opinions: Meta-Contrast
Example Models	Latane & Nowak,(1997); Kacperski & Holyst,(2000); Sznajd-Weron et al. (2000)		Axelrod (1986); Schelling (1978)	Dittmer (2001); Hegselmann et al., (2002)	Amblard & Deffuant, (2004) ; Deffuant, (2006); Franks, et al., (2008)	Salzarulo, (2006)
Description	Opinion is a binary state	Opinion is one value from a finite discrete set	Opinion is a set of values or higher-order complex	Opinion is a single continuous value; opinion change requires small differences	Incorporates certainty as an aspect of influence	Incorporates movement away from opinions deemed dissimilar
Analogs in memory models	All-or-none learning	Decision Field Theory (Busemeyer & Townsend, 1993)	Anderson, (2007); Shiffrin & Steyvers, (1997)	Activation-based accounts of representation (Page & Norris, 1998)		
Empirical Representations	Forced choice preferences	Likert scale or multiple-choice	Concept maps; Latent Semantic Analysis	Group means of forced-choice or Likert-scale questions.		

For example, these systems often viewed an opinion is as a continuous number. The number may relate to a strength of support for an idea, or a perceived worth, or position on a political continuum. An important consequence of these continuous opinions is that any value along a continuum (possibly bounded by extreme levels). By virtue of belief being represented as a continuous value, any intermediate value is possible (by the intermediate value theorem), and so a group belief (averaged across individuals) may be identical to all, some, or none of the member's beliefs. It is also appealing from a modeling perspective, because it can map onto certain classes of physics-based models (e.g., Sznajd-Weron & Sznajd, 2000) and allow some interesting notions of information transmission: Sznajd-Weron and Sznajd (2000), for example, implement the notion that agreement is contagious but disagreement is repulsive. When a set of neighbors agree in their value, their immediate neighbors take on the same value, but when a set of neighbors disagree, their immediate neighbors take on the value *opposite to* the closer member.

However, such representations are limiting in many contexts because opinion, in general, or at least sentiment or support, is they have a more nuanced scale. For example, common methods for measuring opinion involve Likert scales, which require rating a level of agreement on a multi-value scale. However, such models are rarely seen in the wild (although

Galam (2008), discusses 3-state agents, and both Hegselmann et al. (2002), and Stauffer, Sousa, & Schulz (2004) describe ordinal-discrete models), because there is a relatively small step between a multi-value ordinal representation and a continuous representation. Such representations are appealing for several reasons. First, it allows fine-grain and smooth evolution of opinion. The so-called "classical model" illustrates this in which an agent's opinion at time step n+1 is a weighted average of the opinions of others. Without a continuous representation of opinion, this type of dynamic becomes clumsy. Furthermore, it makes it easier to define weighting rules such as the "bounded influence" hypothesis that has emerged as a central tenet of recent models.

The bounded influence hypothesis asserts that opinion change is not simply a process of interacting with others, but is only effective when the neighbor one interacts with is suitably similar. A binary opinion does not allow such a rule because any neighbor who is similar enough in belief already shares that belief. It is a particular kind of weighting rule, because it typically defines a window of influence, and any opinions outside that window will not influence the individual. Hegselmann and Krause (2002) and Deffuant, Neau, and Amblard (2000) have proposed similar versions of this model under the name "bounded continuous opinion dynamics".

Bounded confidence models have a certain appeal in that they capture the intuition that people ignore opinions that are extremely different but are willing to listen to those that are similar. This has intuitive appeal but, as far as we can tell, little direct empirical support other than simulations ability to produce phenomena of interest. One aspect of human influence it misses is that the opinions of others do not always impact us. At times w are strongly convinced of something and cannot be swayed, even moderately. Deffuant (2002) proposed a "relative agreement" model in which, along with opinion value, agents have a "certainty" which specifies how likely they are to be influenced by others opinions. This type of model appears to produce shifts of group consensus formation opinion to extremes (as noted earlier by Moscovici & Doise, 1992), because extreme members of the group will be more certain about their opinion, and attract the consensus. Similar dynamics have emerged from models incorporating social psychological concepts like self-identity theory and meta-contrast (Salzarulo, 2006). This model drives opinion toward similar agents, but away from highly dissimilar agents.

Most of the critical differences between models in the domain of opinion dynamics comes from notions of influence: what are the ways in which an opinion may be influenced by others. Although using both discrete and continuous representations, this has not been a critical differentiator or issue of debate. However, it is reasonable to question whether these tacit assumptions have unforeseen impacts, and whether they represent knowledge in appropriate ways. There are at least two dimensions to consider 1) continuous vs. discrete representations and 2) unidimensional vs. multidimensional knowledge.

3.1.1 Continuous vs. Discrete Belief Assumptions

Aside from a class of Ising-type models imported from physics, most opinion dynamics models use continuous representations of a belief.

This formulation has strengths and weaknesses as a theory of human knowledge representation. It may certainly be a reasonable representation for some classes of knowledge

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and beliefs humans may hold. For example, suppose a buyer and seller needs to come to agreement about a purchase price of an automobile. Opening opinions about the price could differ, and be essentially any positive value. The seller likely has a higher initial value in mind and the buyer will likely have a lower value. Through the exchange of information, they may converge on a common price that could be any value between the two values; in cases such as this, the fact that money is not continuous and must be rounded to the nearest cent (or more likely, the nearest hundred dollars), is only a minor detriment to the model. It is likely that if rounding functions were imposed most of the analysis of such models would not be impacted (as is necessary for most models when simulated using computers.)

Initially, the simplest case of binary belief seems quite limiting. Although it does capture voting behavior, it cannot capture more graded agreement or data very well. However, it is appropriate for a wide range of beliefs that can be articulated; especially those that may vary across cultures.

Problems with assuming continuous beliefs become more apparent when considering other types of knowledge. Starting at a simple level, consider a belief in the truth of the following statements: 1) There is a dog in the room; 2) I had pancakes for breakfast; 3) Dogs make good pets; 4) I want pancakes for breakfast tomorrow. Each could be placed on a scale between 0 (disagree) and 1 (agree), but one would find that some classes of questions (like 1 and 2) can only take on values other than 0 or 1 in contrived situations. These are really discrete beliefs that are either true or false. Examples 3 and 4 could support partial support, but even they could be conceptualized as requiring only agreement or disagreement. Furthermore, whenever selecting a vote or a course of action, this requires a discrete outcome, which may not warrant a continuous underlying representation.

One important factor to consider is that for discrete opinions in general, the average of a set of beliefs is itself a valid belief. For continuous beliefs, it is. This makes opinion drift models tractable because an opinion can be changed an infinitesimally small amount, but it also appears as a crude stand-in for what the models intend to model: influence based on convergence of ideas. Thus, another way to frame a bounded confidence model is in terms of a set of beliefs, and those individuals who are similar overall will interact and exchange beliefs, whereas those individuals who differ on many dimensions will not. This suggests that the focus on univariate belief systems within the opinion dynamics community should be re-examined.

3.1.2 Univariate vs. Multivariate Assumptions

The majority of work in Opinion Dynamics domain focuses on the dynamics of univariate values. However, a number of researchers have explored multivariate beliefs (e.g., "vectors of opinions": Axelrod, 1997; e.g., "vectors of opinions": Weisbuch, Deffuant, Amblard, & Nadal, 2002; Weisbuch, Deffuant, Amblard, & Nadal, 2001). Such models are more similar to cognitive models of knowledge representation that suppose multi-dimensional feature representations for concepts.

One can defend the focus on unidimensional knowledge systems by arguing that the other dimensions (or features) are simply irrelevant, or bound by the same mechanisms. However, this sidesteps important practice in rhetoric and discourse that serves as the inspiration for the field: people simply do not simply state their opinion and expect you to drift toward it; they attempt a reasoned (albeit possibly post-hoc) logical argument for why they believe something and you should too. A logical argument will entail a causal argument, which involves knowledge of a high level of complexity. Because of its focus on unidimensional representations, the field has completely missed the role of argument and reason.

Furthermore, because agents literally have a single piece of information, there is no premium placed on communication. Agents reveal their entire belief system with each exchange. However, if the goal is influence, one may be selective, or one may even lie about one's belief, which the opinion dynamics models do not addressed. More important, in a typical communication, one *cannot* communicate all beliefs. If individual's beliefs could be represented by a complex directed graph, only small snapshots of that network could be transmitted at any one time. What are the limitations that this could place on accurate reproduction of belief systems and what consistent shortcuts would emerge? It is likely that a causal belief system, when communicated, would leave out intermediate but non-critical logic, which then gets replicated. One can think of certain cultural taboos, such as kosher law, in this way. By ignoring complex knowledge, one can miss these types of dynamics.

3.2 Opinion Dynamics and Human Data

In principle at least, opinion dynamics models have the potential to capture observed data of various types. For example, surveys often provide data that can map almost directly into the simple representations used by such models, for forced-choice behaviors (like elections), or sentiment-gathering methods (Likert scale or Visual-Analog scale survey questions). As the human knowledge being represented grows more complex (e.g., causal networks and concept maps), the representations used in this domain become inadequate.

Overall, these models have done a very poor job of making contact with any human data. One reason for this may be the type of instantaneous drift of opinion needed to assess the assumptions of the models is difficult to obtain. However, the field seems satisfied with qualitative demonstrations of effects that seem intuitively reasonable. In order for the field to mature, it must take on the goal of predicting and explaining behavioral data, because it will force practitioners to incorporate the complexity of knowledge at a more central level.

3.3 Limitations of the Opinion Dynamics Approach

Because of tradition, engrained practice, or simply the name, the opinion dynamics literature appears rooted in the notion of how *opinion* is represented, transmitted, and changed. This focus on opinion (in contrast to semantic knowledge in general) has probably occurred for a number of reasons. First, the notion of an opinion is a belief that is in some sense arbitrary and can be disagreed upon. In contrast, it is thought that semantic knowledge is learned facts that are essentially identical for every person, and facts do not appear to have the same type of flexibility. Yet in using such an approach to understand cultural knowledge, the distinction between a fact and an opinion is somewhat arbitrary or at least circular. Does a devout Muslim hold the *opinion* that there is no God but God, or is it a fact? Looking at the belief from an outside culture, one might easily describe it as an opinion, but for an Afghan, every person they know may hold the same opinion. Is an opinion simply a belief about which there is disagreement over a wide enough community? By focusing on opinion and discarding alternate types of belief and knowledge, the opinion dynamics community has missed the ability to identify how there may be different levels of certainty inherent in different types of information, from opinion and sentiment at one end, to coherent facts on the other.

A second reason why this literature appears to favor opinion is that opinions can change and possibly in very small increments. This assumption is so central that few researchers have examined it with a critical eye but it bears closer examination. For example, the field assumes that a political liberal could only become a conservative in a long series of small steps. However, this may not even be the most common way such political conversion occurs. For religious conversion, a complete belief system may be abandoned and another accepted wholesale, rather than in tiny increments.

Another limitation in this domain is the focus on interaction as the driver of change. In contrast, a change in belief may essentially drive interaction, or change may come from self-reflection. For univariate continuous representations, there is no strong reason why self-reflection should cause change, but for complex representations, opinion change could be driven by a desire to maintain internally consistent beliefs, for example.

4.0 CONCLUSIONS

Opinion dynamics offers a fertile domain to understand the social dynamics of belief and belief exchange. Current developments in the field are moving models toward more psychological accounts of influence, but the representations remain impoverished and the connection to behavioral data is rare, which severely limits the potential of the field.

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APPENDIX B: Paper in Cognitive Science Workshop

Incorporating Representation When Modeling Cultural Dynamics: Analysis of the Bounded Influence Conjecture

Shane T. Mueller (smueller@ara.com), Ben Simpkins (bsimpkins@ara.com), and
Louise Rasmussen (lrasmussen@ara.com)
Klein Associates Division, ARA Inc
Fairborn, OH, 45434, USA

Abstract

A number of social modeling and simulation approaches have attempted to understand the exchange and convergence of ideas based on simple representations and rules for information exchange. However, this focus on finding emergent properties of simple agents and rules has led this research area to avoid handling many genuinely cognitive phenomenona, and ignore many important questions regarding the transmission of cultural ideas. We propose that one deficiency is in the treatment of knowledge in very simple structures, in contrast to the richness of true cultural knowledge. This simplification has lead to the bounded influence conjecture, which we show is not necessary to produce distinct groups of disagreement within an interactive group. Instead, we hypothesize that aspects of the space of valid knowledge states can create a similar outcome. We provide a demonstration of this hypothesis through simulations in a multi-agent interactive model.

Cultural as Shared Knowledge

One common perspective on culture is that it consists of shared beliefs, attitudes, mental models, and customs developed by a group of individuals who interact frequently. This view (cf. Atran, Medin, & Ross, 2005) is somewhat at odds with perspectives of culture that focus on demographic or geographic variables, because it asserts that culture is primarily a phenomenon of cognition, rather than behavior.

A number of methods have been developed to measure this notion of culture-as-shared-knowledge. Although initial perspectives focused on culture as consensus (e.g., Cultural Consensus Theory; Romney, Weller, & Batchelder, 1986; Romney et al., 1996; Romney, 1999), more recent developments have allowed culture to be characterized by a variety of distinct opinion groups (e.g., Cultural Mixture Modeling; Mueller & Veinott, 2008). These approaches focus on formal statistical methods to represent culture as shared knowledge, and enable detailed cultural models to be identified for interview and survey data.

Simulating Cultural Knowledge and Consensus

The culture-as-shared-knowledge perspective is also present among researchers working with large-scale simulations. For example, Axelrod (1986) famously define a framework for simulating the exchange of ideas in a multi-agent system that enabled formation of local consensus but global diversity. Here, a local group of agreement could be considered a single culture, but the simple act of idea exchange did not create a global monoculture. One important driver of this was the assumption of homophily or bounded influence: an agent is only willing to listen and be influenced by viewpoints that are sufficiently similar to its own. In those models, similarity is both a function of geographic closeness or closeness in a social network (agents only talk to adjacent or nearby agents) and conceptual similarity (agents only talk to agents who are identical on a minimal proportion of features). Thus, after distinct groups emerge, it becomes impossible for members to jump from one group to another, because they simply refuse to be influenced by the extreme beliefs of the other groups.

Opinion Dynamics and Representation

In recent years, a community of practice has emerged in the field of opinion dynamics (see Lorenz, 2007, for a survey of the field), which has explored many of the same ideas as Axelrod, perhaps without arguing the models are cultural. Nevertheless, if one views culture as a consensus of ideas, researchers in this community models the process by which the consensus may develop. In addition, if one takes the view that culture can be a diversity of ideas, this community also models the conditions under which consensus fails to emerge.

Although earlier work by Axelrod used somewhat complex knowledge representations (a multi-dimensional vector containing numbered tokens), the opinion dynamics community has focused primarily on simpler representations that take their inspiration from physical models (see Ball, 2003 for a broad review). So, some opinion dynamics models represent a single 'opinion' as taking on either 'agree' or 'don't agree' (or possible 'disagree'; e.g., Latane & Nowak, 1997; Kacperski & Holyst, 2000, Sznajd-Weron & Sznajd, 2000). These models map closely onto the so-called "Ising spin model", which has been used for years to model physical ferromagnetism. As a consequence, it has many well-understood properties. However, it prevents incorporating any interesting notion of bounded influence, because other members of the population are either identical to an agent, or completely different. Any bound on influence in these models has no effect, because those who are similar to an agent are identical to the agent, and so cannot change its beliefs.

More recent advances in the field have begun to incorporate notions of bounded influence, but to do so, they required moving to a knowledge representation that is on a multi-value scale. The most common versions assume support of an opinion takes on a rational value between 0.0 and 1.0 (Dittmer, 2001; Hegselmann & Krause, 2002). When the influence threshold is large enough, a consensus typically emerges; when the influence threshold is smaller, multiple distinct islands of opinions may emerge. Extensions of these models have dealt with rules of bounded influence that are even more complex (Amblard & Deffuant, 2004; Deffuant, 2006; Franks, et al., 2008), and have only recently begun to take seriously psychological functions within their models (cf. Salzarulo 2006; Kopecky, Bos, & Greenberg, 2010).

The bounded influence conjecture is interesting, because it does not appear to be inspired by any documented cognitive or social phenomenon, and it is used to create an effect (distinct groups of disagreement) that is not an empirical phenomonon, but simply a reasonable possible state of the world. To be fair, Mueller & Veinott's (2008) cultural mixture modeling advocates the possibility of multiple distinct communities of belief within a culture, but it does not assume that this happens for a single dimension, but rather as an emergent cluster over a set of beliefs.

One explanation for the bounded influence conjecture is that it occurs because the impoverished representations of knowledge present in opinion dynamics models prevent a richer understanding of knowledge, disagreement, and the relationships between knowledge states. In a standard opinion dynamics model, the simplistic methods of knowledge representation coupled with simple interaction/influence means that in a typical standard situation, all agents will eventually align to form a consensus. These simple models are valuable because they are amenable to formal proofs of convergence, but their simplicity may necessitate assumptions (such as the bounded influence conjecture) that are not necessary and not warranted by the psychology of influence. Without bounded influence, given enough interactions, a system will typically converge to a consensus.

Yet cultural knowledge is much richer than is supposed by these models. If we allow just one level of increase in the complexity of data, we find cultural surveys like the Afrobarometer (e.g., Lewis, 2007), and the General Social Survey (e.g., Davis et al., 1998) that at least require one to view culture as a set of values in some type of space. But even more complexity can exist, which presents additional interesting possibilities.

For example, perhaps some sets of ideas depend on one another, or imply one another. Some sets of ideas may be internally consistent, while others are not. Perhaps social customs prevent discussion and influence about some types of concepts (politics and religion) but not other (television shows). These possibilities suggest an intriguing alternative: perhaps the bounds of influence are not parameters of an individual's willingness to listen to another's opinion, but rather are parameters of the viable states of knowledge.

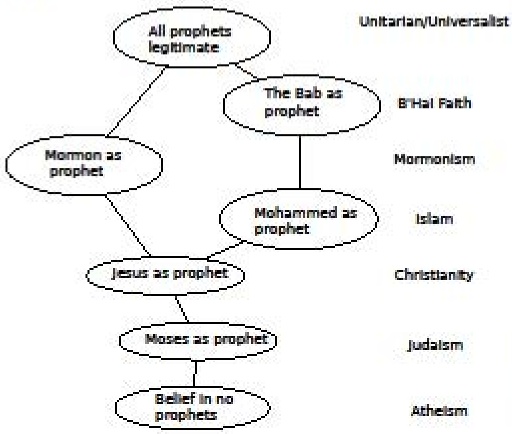
Knowledge Spaces as a means to represent complex knowledge

Researchers in areas of education and measurement have developed formal algebras for representing complex knowledge systems that may provide a means to understand beliefs across a group (cf. Albert, 1994; Doignon, 1999; Falmagne et al., 2006). According to this research, one can represent a set of concepts as a partially-ordered set of knowledge states, such that any higher state requires the attainment of a lower state, or in other words, attainment of one state implies attainment of all lower states. A common example includes a student's attainment of the mathematical skill of complex division, which requires master of subtraction and simple division. If one knows the student understands complex division, one can assert that she also understands subtraction. These states form a lattice: a set of nodes in a network that are connected if one node implies understanding of another.

Wiley and Martin (1999), Martin and Wiley (2000), and Butts and Hilgeman (2003) have expanded and extended these ideas to characterize a knowledge lattice across a social group. Now, knowledge in this case is not just abstract, but the set of knowledge states found among a population is used to form the knowledge lattice. Each individual in the group lives within one of the nodes, and the network describes the variety of beliefs within the group. For example, Figure 1 shows a potential knowledge lattice for a set of world religions. Here, we describe religions in the Judeo-Christian-Islamic traditions based on the prophets they believe in. A vertical connection implies belief in everything connected lower than the node. So, Christians believe in Moses and Jesus, Muslims believe in Moses, Jesus, and Mohammed, and so on. Each node is closely affiliated with a world religion, and the movement between nodes involves adding or removing a single belief from ones belief system. The set algebra of course could represent a religious group that, for example, Moses was not a prophet but Jesus was, or that both Mohammed and Mormon were prophets but the Bab was not. This example highlights how, for a set of beliefs, there may be a more likely path from one belief to another (Conversion from Mormonism to Islam may be unlikely), or a set of beliefs happens to be inconsistent (e.g., Mormon was a prophet but Jesus was not).

A knowledge space may have a similar effect on preventing consensus that the bounded influence conjecture does, but without making the bounded influence assumption. Instead of simply saying that one will not be influenced by individuals who have an extremely different set of beliefs, one might hypothesize that movement between beliefs can only happen when the influence process lands a person in a valid belief state. So, in our example, perhaps a Jew and a Universalist will indeed listen to one another, and although they are at opposite ends of the belief spectrum, it may be possible that

Figure 1: Knowledge space characterizing several world religions. A connection implies that the higher-level concept in some sense requires or implies the beliefs at lower levels.



one moves toward the other *as long as they end up in a valid belief state*. So, the Universalist may not convert to Judaism, but may be convinced that aspects of Mormonism are false. However, if there is no consistent set of beliefs that allow one to hold "every religion but Mormonism is acceptable", they may not move away from their initial knowledge state. This provides a mechanism for belief clustering and consensus avoidance that critically depends on the knowledge structure, not simply arbitary sharing rules.

Simulation Model of Influence Dynamics via Belief States

To test the hypothesis that consensus and disagreement behaviors could arise from properties of the knowledge system rather than a parameterized bounded influence, we implemented a simple simulation to test the principles.

We began by creating a knowledge space based on twenty binary features, and selecting fifteen distinct states within the space. Figure 3 shows the space selected, and Table 1 shows the binary feature representations for each state.

Each simulation involved 100 agents, initialized with a specific distribution across knowledge states. We assumed that these fifteen states were the only valid states an agent could hold, but did not make assumptions about why. At each step of the simulation, a pair of agents were chosen randomly, and with probability $\mu = .3$, each feature of each agent was changed to be

Figure 2: Knowledge lattice used in present simulations. Each of the fifteen states corresponds to a binary vector of twenty features. An arrow implies that a higher node contains all the positive (1) values that a lower node contains.

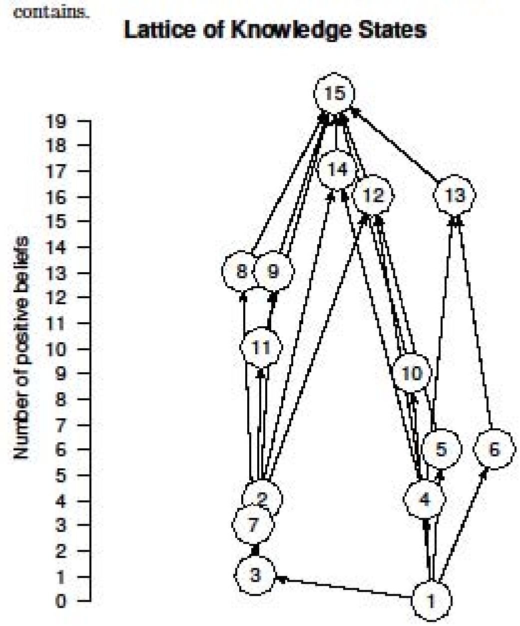


Table 1: Feature representation of the fifteen knowledge states in Figure 1.

Knowledge State	Knowledge
1	00000000000000000000
2	00001000001001000010
3	00000000000000000010
4	00001100100000100000
5	00100100010101100000
6	01000001001111000000
7	00011000000000000010
8	00100111111110011110
9	10010111010111100111
10	01000001111000011101
11	01100011011100010011
12	11101110111101111110
13	11011111111111110001
14	11111110111110111110
15	11111111111111111111

identical to the other agent's. At the end of this exchange, each agent's new knowledge state was examined, and if it were identical to one of the predetermined knowledge states, this new state was retained. This last restriction forces all agents to live somewhere in the predetermined knowledge space. We computed the distribution across knowledge states after every ten exchanges to visualize the evolution of belief across time.

Figure 3 shows a fairly typical simulation for a starting configuration in which individuals were uniformly spread across belief states. Because there are many individuals at points along the path from one belief to another, initial conditions such as this tend to converge to a single belief state or a pair of adjacent states. The simulation continued 40000 exchanges, after which 86 agents were in state 1, and 14 were in state 13. Mixed initial configurations typically converge to a single belief state, near the extreme, although two adjacent belief states can be fairly stable. We have not witnessed convergence to a compromising belief state.

Opinion dynamics simulations often start out in random configurations, but this is probably unrealistic–we are all born into a society that has established norms and beliefs. Another starting configuration to consider is one in which individuals are in either one or another of the most extreme states (akin to the organization of the U.S. Senate, as discussed by Mueller & Veinott, 2008). Figure 4 shows the evolution of belief over time for such a starting configuration. The belief distribution remains fairly stable, at the two extremes of the belief spectrum (states 1 and 15). Although other states do emerge in their proportion, these quickly get subsumed into the larger more extreme groups.

Summary and Discussion

In this paper, we demonstrate how one common assumption about the way information is shared among people (the bounded influence conjecture) may not be a property of influence per se, but rather could be an aspect of a more complex network of potential knowledge states. This highlights one of the benefits of taking cognition more seriously when modeling social science. Previous assumptions about bounded influence were made in order to produce a behavior that seemed reasonable, but apparently without reference to psychological study of influence.

We believe that there are additional benefits that can be gained from considering more complex knowledge structure as the medium of cultural exchange in opinion dynamics models. For example, much cultural knowledge can take the form of cultural schemas and mental models Cultural Schemas/Models (e.g., D'Andrade, 2001), causal models (Rasmussen, Sieck, & Smart, 2009), decision trees (Gladwin, 1989), scripts (Ryan, 1996). By considering more complex representations, one needs to begin to consider important factors such as how much and what type of information is shared (rather than sharing all beliefs at each interaction), whether there are core aspects of a belief system that logically or traditionally cohere, and the ways messages might be created by one who is attempting to influence another, such that it has the greatest chance of changing their mind.

Acknowledgments

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Figure 3: Proportion of different knowledge states of the population over time

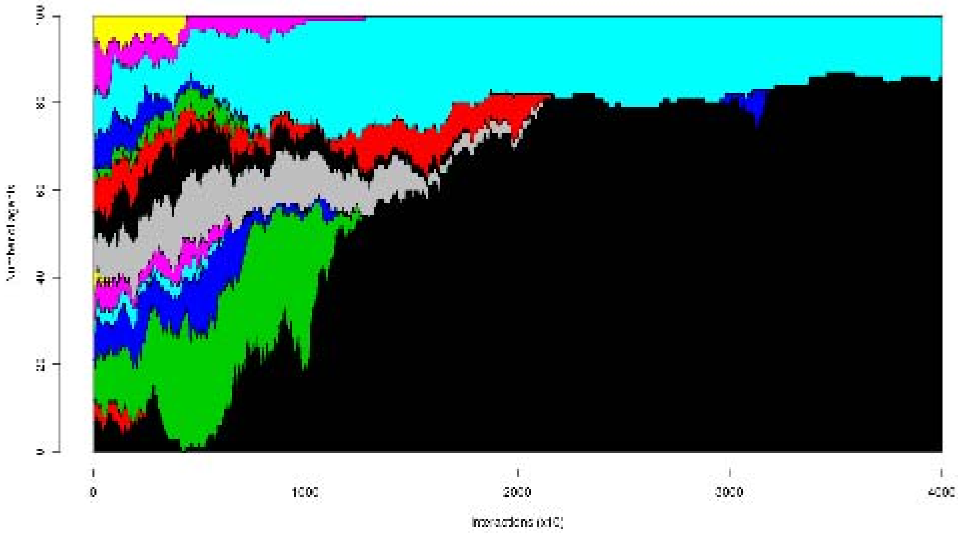
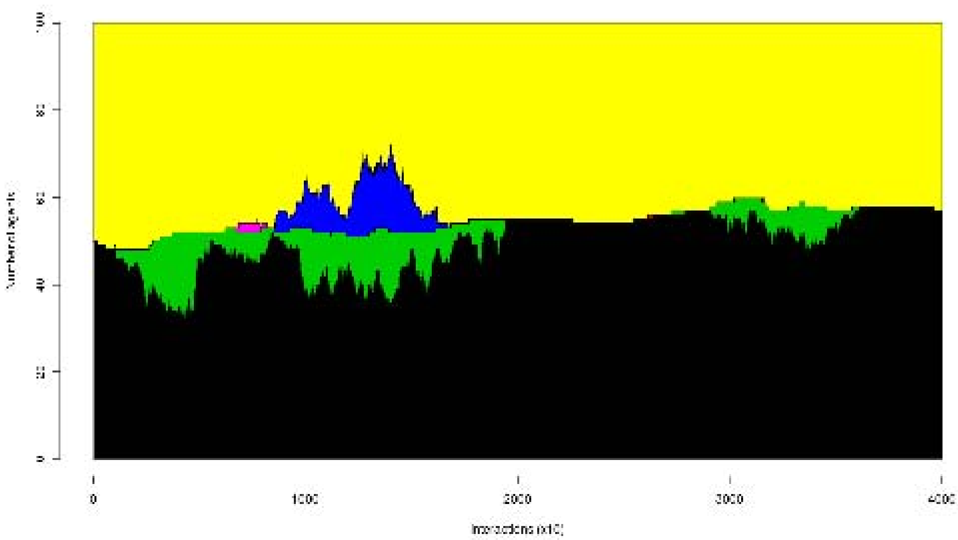


Figure 4: Proportion of different knowledge states of the population over time. Initially, all agents were in only the two most extreme states.



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APPENDIX C: Submitted Paper on Opinion Dynamics

Noname manuscript No.
(will be inserted by the editor)

Cognitive Perspectives on Opinion Dynamics: The Role of Knowledge in Consensus Formation and Group Polarization

Shane T. Mueller

Received: date / Accepted: date

Abstract Standard approaches to modeling the dynamics of opinion within interacting groups have typically assumed that agents have an implicit influence bound, such that they ignore opinions that differ from their own by some bound, and thus converge to distinct groups that remain uninfluenced by other belief groups. This paper suggests a cognitive source for this phenomenon: the need for consistency within a set of related beliefs. Via simulation, this source is shown produce convergence dynamics similar to the bounded influence conjecture, while also producing the robust social psychological phenomenon of group polarization (which the bounded influence conjecture does not produce by default). Finally, the two theories are compared based on their assumptions, highlighting ways in which their differences can be tested via empirical research.

Keywords opinion dynamics · knowledge spaces

1 Cognition and Knowledge Representation in Social Simulations

In the research area sometimes known as opinion dynamics, a growing number of modeling paradigms have sought to understand how insights from mod-

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S. Mueller
Applied Research Associates
1750 Commerce Center Blvd, Fairborn OH 45324
Tel.: +937-873-8166

E-mail: smueller@ara.com

els of physical systems can inform our understanding of the formation and transmission of opinion and belief within organizations, groups and societies. Much of this progress has centered on simple agents with simple knowledge, interacting according to simple rules that together produce simulated behavior resembling complex phenomena observed in or hypothesized about the real world. For example, in statistical mechanics, the Ising model (see Brush, 1967) was developed to examine phase change in ferromagnetic physical systems. Such models can be viewed as analogies to social systems, in that a group with initially distinct opinions may converge to a consensus because of their close interaction, just as a lattice of polarized particles may align their polarity and come to a stable state.

Yet the simplicity of these simulations comes at a cost. Although simplified assumptions about knowledge representation make simulation simpler and proofs of convergence possible, these sometimes force theorists to make ad hoc and unfounded assumptions about interaction rules in order to create interesting convergence distributions. For example, by using a simplistic knowledge representation akin to the Ising model in which all agents are completely described by whether or not they hold a belief (i.e., they are either 0 or 1), there is little room for understanding influence and belief change at an individual level, other than change from complete agreement with a premise to complete disagreement. Unfortunately, translations of physical models to social systems often require assumptions governing both belief representation and interaction rules that are unprincipled from a psychological perspective. These are sometimes simply atheoretical conveniences that are assumed in order to produce end-state distributions that are intuitive and reasonable. But these assumptions sometimes replace psychological theory, producing an observed behavior but not providing a reasonable or testable account of the phenomena.

Convergence distributions and phase transitions might be influenced by a number of psychological sources that are outside the realm of physical models. These might include concepts as fundamental and cognitive as attention, memory, the structure of knowledge, the need to maintain self-consistence. Looking to psychological and cognitive sources for accounts of these phenomena may prove fruitful, because it can provide important insight into the types of data that could validate group-level models. So, although the reliance on physical models as inspiration for organizational phenomena has been fruitful, this has sometimes come at the expense of the insights that cognitive theory may provide regarding group behavior and processes.

In this paper, I will examine several common phenomena in this literature that have been attributed to interaction rules in physics-based simulations. I will propose cognitive and knowledge-based accounts that can explain these phenomena, and also identify testable hypotheses which can help discriminate alternative theories. The relevant phenomena involve belief transmission within a group, and center on phenomena of (1) consensus formation, (2) the formation of distinct stable cultures of a belief within an interacting group, and (3) the group polarization phenomenon.

1.1 Consensus formation in interacting groups

Typical models of opinion dynamics assume that beliefs are fragile, and can be be easily influenced through interactions and discussions with others. Such models can account fairly easily for phenomena such as fads and fashions, information cascades, and various examples of herd mentality and groupthink (see MacKay & Baruch, 1932, for some remarkable examples). Furthermore, such models can be deployed in automated distributed intelligent systems where consensus formation is necessary, but there is no central leader which can dictate a group decision (see DeGroot, 1974). A basic simulation showing consensus formation or "collective cognitive collapse" (Parunak et al., 2008, 2009; Parunuk, 2009) is shown in Figure 1.

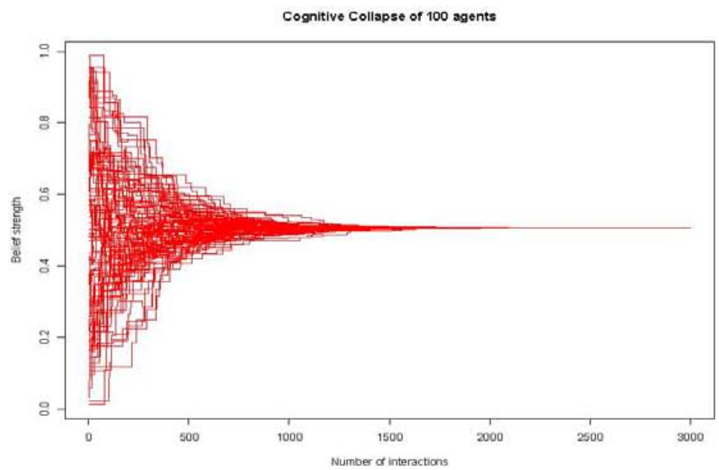

Fig. 1 Timecourse of convergence of a simple interacting multi-agent system with indiscriminite influence. The population quickly converges to a common belief (which is typically moderate).

In this simulation, the representation dimension is expanded from the simple binary 0-1 state discussed earlier to a continuous value between 0 and 1. This representation has been used extensively in the opinion dynamics literature (see Lorenz, 2007, for a review of the history of these assumptions). 100 agents were given random initial states on a continuous value between 0 and 1. On each step, two agents were chosen, and their current states were compared. New beliefs were chosen for each agent so that it moved slightly toward the other chosen agent's belief. The results match what should be an intuitive result: the population quickly converges to a single state, and has no ability to escape that belief after convergence.

Although such a model has applications, it fails to capture many observations about beliefs in human groups. Most specifically, in human groups and societies, individuals with extreme beliefs can be recalcitrant, such that no amount of talking and discussion will allow them to come to an agreement. Although there are many ways in which groups, families, organizations, and societies reach agreement about specific ideas, there are always areas in which a group will not agree. Belief landscapes may be as divisive as they are consensus-based. Thus, opinion dynamics models of the kind just described have often been augmented in a number of ways to prevent convergence. The most common assumption has been what I will refer to as the "bounded influence" conjecture (often called the "bounded confidence" assumption).

1.2 The Bounded Influence Conjecture

One of the central hypotheses in opinion dynamics is the "Bounded Influence Conjecture". This hypothesis has come to form a critical core assumption of much research on opinion dynamics, and in turn many agent-based simulations of social knowledge. The basic assumption can be traced at least back to Axelrod (1997), but it has been explored and discussed extensively in the past decade, (e.g., Amblard and Deffuant, 2004; Deffuant, 2002; 2006, Carletti et al., 2006; Franks et al., 2008; Hegselmann & Krause, 2002; Lorenz, 2006; 2007; Fortunato, 2005; Fortunato & Stauffer, 2005).

The bounded influence conjecture is typically operationalized within agent-based simulations, where agents have belief structures that are represented on a unidimensional bipolar continuous scale as in simulation presented earlier, often anchored by 0.0 and 1.0. or -1.0 and 1.0. Certainly, some researchers have explored more complex representations (e.g., Flache & Macy; 2006), but to the extent that there is a standard model, it uses a single continuous dimension. As described before, the basic models allow interaction between any agents, which causes each agent to shift its beliefs toward the agent it interacts with (at least occasionally). Bounded influence institutes an additional bound (e.g., δ), such that the belief shift is only carried out if the two belief values differ by less than δ. The bounded influence conjecture tends to produce stable groups of agreement that are at odds with one another, within a single larger belief space.

Although it has been described in a number of different ways, one simple way of stating the bounded influence hypothesis is that we ignore or are not influenced by beliefs that are extremely different from our own. It is perhaps a formal implementation of the concept of "groupthink", and resonates with aphorisms like "birds of a feather flock together", and so has much intuitive appeal. But it is also problematic, for both theoretical and empirical reasons. For example, there is little direct empirical evidence for the conjecture, and indeed there are reasons to believe that the opposite can hold. Also, the conjecture has weak explanatory power, because it essentially assumes the effect it attempts to produce. Furthermore, on its own, it fails to produce one of the most common empirical phenomena related to group belief processes: group polarization. These deficiencies may call for a rethinking of the bounded influence conjecture, and merit replacement with a cognitive and psychological notions. Furthermore, I will show that one simple cognitive account is powerful enough to produce these effects without the bounded influence conjecture: consistency of belief within a knowledge space.

Criticism 1: Lack of empirical evidence There is certainly anecdotal evidence in support of the bounded influence conjecture. Political debates often appear to be a discussion among two groups with polar opposites beliefs, who simply ignore the other's arguments. Similarly, a common finding in the social psychology literature is one of in-group bias: preferential treatment given to those who belong to the same group (Tajfel, 1970), with group often defined by heritage, geography, affiliation, etc.

Yet many of these behaviors, even if accepted as true, could have other explanations. The bounded influence conjecture should not be confused with homophily, which is the tendency to interact with those who are generally similar by external measures. This is akin to the distinction made by Lazarsfeld & Merton (1954) between *status* and *value* homophily. Furthermore, theories of homophily describe whether two people or agents will associate; not whether they will take on one another's beliefs. So, in-group effects may not stem from shared beliefs per se, but instead from group membership. In fact, in-group effects can be found for even arbitrary group memberships, where beliefs are uncorrelated with group identity (e.g., Ferguson & Kelly, 1964; Brewer, 1979). Thus, homophily may still mediate opinion dynamics, but perhaps opinion does not mediate homophily.

Furthermore, for many of the anecdotal cases that appear to support the bounded influence conjecture the best, they can also be argued to violate the assumption. The tradition of western political discourse and debate means that those with extreme views often do know and listen to the opposing views quite well, better than those with moderate views. Opposing views are carefully studied and dissected in order to offer counter-arguments. And the bounded influence conjecture is not really about extreme views: one holding a moderate view may ignore extreme views if the bound is small enough, just as one holding an extreme view may ignore a moderate one.

Finally, a number of classic studies in decision making suggest that the opposite of bounded influence might be true. For example, heuristics-and-biases research has identified the "anchor and adjustment" phenomena (e.g., Kahneman & Tvevrsky, 1973), in which extreme initial biases have large impacts on outcomes. If bounded influence were really at play, one might expect extreme anchors to have less of an influence than intermediate anchors. Although such effects have sometimes been found (see Wegener, Petty, Detweiler-Bedell, Jarvis, and Blair; 2001), and although one may argue that "anchor and adjustment" is not valid for true 'opinion' dynamics, greater influence of extreme anchors has been demonstrated in adversarial opinion situations, such as the courtroom (e.g., Englich, 2006).

Criticism 2: Weak explanatory power Logically and theoretically, there are also problems with the bounded influence conjecture, because it embodies a somewhat circular process. Consequently, it provides only a weak explanation of the behavior it seeks to account for.

The notion that extreme opinions are ignored is somewhat implausible, because one first needs to attend to them in order to determine whether they should be ignored. If one uses in-group status, media channel, social network, or other cues to filter out opinions, then filtering is not based on opinion (and so the process is not based on bounded influence). Of course, it is not difficult to contrive a process by which one first attends to an opinion in order to determine whether it should be ignored, and then discounts the information if it is deemed too extreme (see Mueller, 2009). Yet research suggests that discounting might not be applied optimally, and discounted memory traces are difficult to ignore, even when discredited (see Bush, Johnson, & Siefert, 1994).

Bounded influence also makes predictions that changes in attitude must be gradual, drifting smoothly along the continuum from one extreme to another as one interacts with individuals of different beliefs. But this is in opposition to the scientific literature (Hayes et al., 2007), and phenomena such as religious and political conversion or deconversion which involve wholesale adoption of a large set of beliefs distinct from those previously held. In addition, the conjecture doesn't just assume that those on one extreme ignore those on the opposite extreme: in terms of political ideology, it can assume that conservatives ignore moderates, and moderates ignore both liberals and conservatives.

A more important criticisms, however, is that the bounded influence conjecture essentially assumes the phenomena it is trying to explain. The phenomenon of interest is that multiple distinct stable consensus groups can exist within a population. To produce this, the bounded influence conjecture relies on an assumption that will maintain such a configuration if it exists: if you fall into a "well" of opinion, you can only listen to those with identical views, and so there is no chance of changing that view. The approach might be defended on the basis that it attempts to explain how these wells emerge, but even then, the account falls short, because they typically start with 'random' configurations of belief that never or rarely exist in the real world, becaus we are born into a society with well-accepted belief systems.

Yet there are other possible obstacles to consensus formation. One I will explore is the importance of holding consistent beliefs. For example, in the United States, political parties ascribe to a series of beliefs and attitudes that are interrelated, and sometimes attributed to a single underlying principle. The Republican party officially opposes abortion, opposes nationalized health care, supports gun rights, opposes unionized labor, and supports capital punishment, and so on, while the Democratic party has opposite stances on each of these issues. While there are certain members of each party who differ from their party consensus on a small number of issues, (see Mueller & Veinott, 2008), views are associated with one another, either logically or by tradition, to such an extent that an individual may not be able to repudiate one belief without disavowing others. As Rudolf Giuliani has shown, gun rights are not necessarily opposed to abortion rights (Santora & Nagourney 2007), but they are so strongly associated.

Such a need for consistency may underly the observed recalcitrance of opinion typically modeled with the bounded influence conjecture. According to this view, opposing opinions are not edited or ignored, based on the beliefs of the agents on interacts with. However, one must consider an entire belief system rather than just a single opinion. If the resulting belief results in an inconsistent set of opinions, movement to that state may be prohibited as taboo or forbidden. Later in this paper, I will examine opinion dynamics models that rely on this assumption, and I will show that it can produce the same types of behaviors that the bounded influence conjecture is used for. But first, I will examine the group polarization phenomenon, which suggests the bounded influence conjecture is inadequate for explaining group opinion dynamics.

1.3 Group Polarization

A related phenomenon that has been discussed in both the social psychological literature and the opinion dynamics literature is known as group polarization (see Fraser, 1971; Myers & Lamm, 1976). This describes the phenomenon that a group of individuals will arrive at a consensus that is more extreme than their average initial beliefs when allowed to engage and discuss the issue at hand. Most recent opinion dynamics models produce distinct subcultures of belief that differ, but without additional assumptions, these converge to moderate beliefs rather than extreme ones (Hegselmann & Krause, 2002; Weisbuch et al., 2002; Weisbuch et al., 2003; Deffuant et al., 2004; Lorenz, 2006). Additional assumptions are needed to produce group polarization, and these include the presence of unwavering extremists who draw consensus toward themselves, asymetries in the influence bounds so that moderates are more likely to listen to extremists than vice versa, and other similar interaction rules. In the subsequent simulations, I will demonstrate how a knowledge-consistency based approach provides a novel explanation that makes none of these additional assumptions necessary.

Next, I will describe a simulation approach that places knowledge structures and knowledge spaces constrained by a need for consistency at the core of opinion dynamics. I will illustrate how these knowledge spaces can be used to constrain the types of beliefs an individual might hold, and thus provide a knowledge-based means for stable group segmentation and group polarization.

2 Simulations

To explore the role of knowledge in social simulation, I assumed that opinion-based beliefs are a multidimensional set of binary beliefs (e.g., agree versus disagree) on a number of related issues. Without losing the spirit of the model, one could assume that beliefs could take on a number of discrete positions on a particular issue (e.g., if there were three, support, ambivalence, and opposition). However, this approach is at odds with the typical assumption that opinion strength is an infinitely-discriminable scale between two opposite extremes (see Mueller & Weidemann for an empirical demonstration suggesting humans are not capable of even consistently discriminating between discrete levels of confidence about a perceptual state). However, even this distinction is somewhat soft, because one can easily create a scale of arbitrary precision by combining sets of binary opinions, just as one can represent any irrational or rational number with arbitrary precision using a set of binary digits.

Furthermore, the model assumes that the values of these opinions are not arbitrary, but rather are valenced with some higher-order set of traditions or principles, to represent agreement with one consistent sets of beliefs, and disagreement with a second.

In the simulations, a knowledge space is first constructed which defines a set of 'legal' or 'consistent' combinations of beliefs. In the simulations, 20 binary features are used to describe beliefs, which provides $2^{20} = 1,048,576$ possible knowledge states within a knowledge space. From these possible states 15 unique states were sampled along the valence spectrum (each simulation used a different sampling method), but the two most extreme states were always chosen (i.e., all 0 and all 1). Different simulations use different schemes for sampling these states. The knowledge space lattice (see Doignon & Falmagne, 1985; 1999) describing these states can be formed through complement arithmetic (see Wiley & Martin, 1999; Martin & Wiley, 2000; Butts & Hilgeman, 2002), in order to identify which states are subsets or supersets of other states.

2.1 Simulation 1: Convergence and polarization in distributed knowledge spaces.

The first simulation shows how using a knowledge space can produce one of the main phenomena used to justify the the bounded influence conjecture. In this simulation (and the others) the first step was to create a knowledge space (as shown in Figure 2) based on 20 binary features with 15 total knowledge states, always including the two most extreme states (i.e., all [00000000000000000000] and all [11111111111111111111]). Each knowledge state was chosen by first sampling a single value p with a uniform random distribution between 0 and 1, and then using p to determine whether each of 20 binary features should be 0 or 1 (0 with probability p, 1 with probability $(1 - p)$).

This approach tends to create nodes distributed along the continuum between the two extremes, allowing both moderate and extreme viewpoints

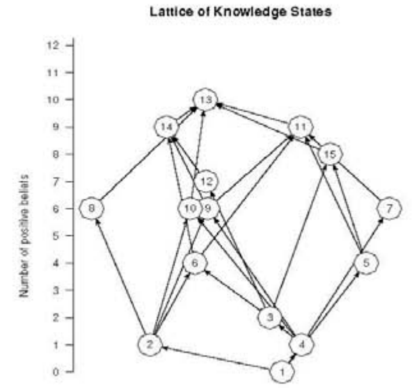

Fig. 2 Lattice describing a typical knowledge space created by sampling belief states distributed uniformly across the range of agreement/disagreement with an extreme view. Arrows indicate that a higher-level state fully encompasses the beliefs of a lower-level state.

to emerge. Furthermore, because there are relatively few possible knowledge states at the extremes (compared to the bulk of possible states that are moderate), this uniform sampling over-represents extreme views, especially considering that the most extreme views are always represented. In contrast, if states were chosen at random, the distribution would approximate a binomial distribution with $p = .5$.

For each simulation, 100 agents were distributed randomly across the fifteen knowledge states, and during the simulation they were allowed to interact and influence belief according to the following procedure:

- Two agents were chosen at random to interact, without regard to individual beliefs.
- Each binary belief element for one agent was independently selected for inclusion in the "discussion" (with probability $\mu = .3$).
- A new candidate belief for the first agent was created by changing its discussed beliefs to those of the other agent in the discussion.
- If the new belief state was valid (that is, it was one of the pre-selected belief states), this new state is adopted by the agent.
- Steps 2-4 (one cycle) were repeated for the second agent in the discussion.

This process was repeated many thousands of times. Every 1000 cycles, the distribution over knowledge states was examined for signs of convergence, and the simulation was discontinued either once a convergence criterion was met, or 125,000 rounds were simulated. The convergence criteria were: (a) the population were all in a single knowledge state, or (b) the population was distributed across an identical set of knowledge states for 25 consecutive 1000-round cycles, ignoring any states with five or fewer agents. These low-frequency states were ignored because there is always opportunity for singleton agents to jump to a third state whenever more than two states exist, and since we evaluated convergence only every 1000 cycles, a strict convergence criterion would ignore some of these small deviations that happened between samples anyway.

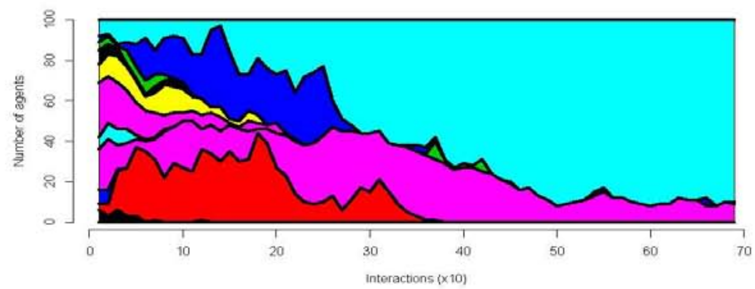

Fig. 3 Dynamics across a single sample run of Simulation 1. At each horizontal position, the vertical distance between lines represents the proportion of agents with a particular belief. System meets convergence criteria after about 70,000 iterations.

Figure 3 illustrates the dynamics of a single simulation across time. Each vertical slice represents a distribution across states, from one extreme (all 0 features at the bottom) to the other (all 1, on the top). Over time, agents converge to fewer states, until by about 35,000 interactions they are primarily located on just two states. These two states are both fairly extreme, with one dominating. The system met the convergence criteria by about 70,000 iterations, although had it gone longer, it would have likely eventually converged to a single state.

Figure 4 shows two aspects of the average behavior of this system across 1000 runs. First, out of 1000 runs, only 69 failed to meet either of the convergence criteria after 125,000 rounds. The solid black line in the figure illustrates the cumulative convergence distribution. Most simulations did not converge until about 50,000 iterations, but most had converged by 100,000 iterations. Figure 4 also shows the number of states converged to. The 0 state indicates non-convergence; and 1 through 4 indicate that the simulations converged to between 1 and 4 groups (with more than five agents). Most often the system converged to two states, although a substantial monority also converged to 1 or 3 states.

It is also important to examine the states that the simulations converged to. In traditional opinion dynamics models, groups of agents tend to converge to a opinions at the center of a "basin" whose size and extremity is controlled

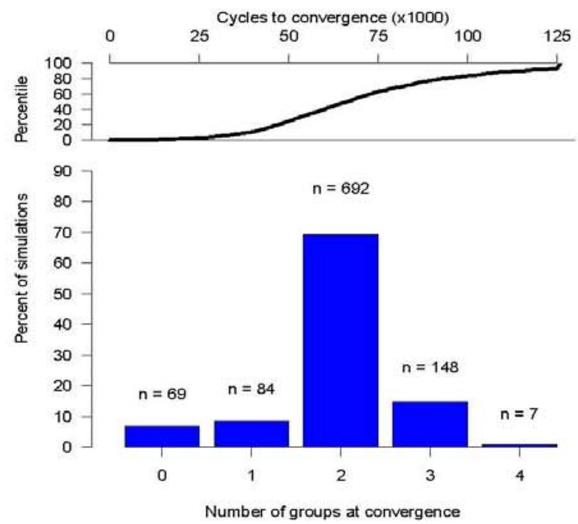

Fig. 4 Depiction of the convergence of 1000 simulations in Simulation 1. All but 69 simulations converged after 125,000 cycles, and most simulations converged to two groups.

by the bounded influence parameter (see, for example, Hegselmann & Krause, 2002). Thus, we might expect groups to converge to the center of the belief space, especially because agents in this simulation are essentially blind to the extremeness of their own and others opinions. In other words, once the knowledge state is set up, beliefs could be arbitrarily recoded from 0 to 1 or vice versa, and the simulation would produce the same result because the mean extremeness of a belief is never computed or used to guide behavior. Figure 5 shows that in contrast to many previous models, and despite the fact that agent's don't explicitly use extremeness of belief, they to converge to the more extreme belief states. In the figure, the horizontal axis shows the spectrum of belief for possible belief states—essentially how many of a state's binary values were 1 versus 0. The thick black line with round symbols indicates the probability that a knowledge space contained a knowledge state with N positive features. Because there were always 15 states and the two most extreme were always present, they have on average 1.0 per simulation, and all other cases are approximately $13/19 = .68$. For comparison, the solid grey line shows the distribution of potential knowledge states across the belief spectrum, with the great majority falling in the middle region. The thin U-shaped line shows the probability that a state was held by more than five agents at convergence. Here, despite the initial uniform distribution across the knowledge space, the agents converged to the extreme ends of the space.

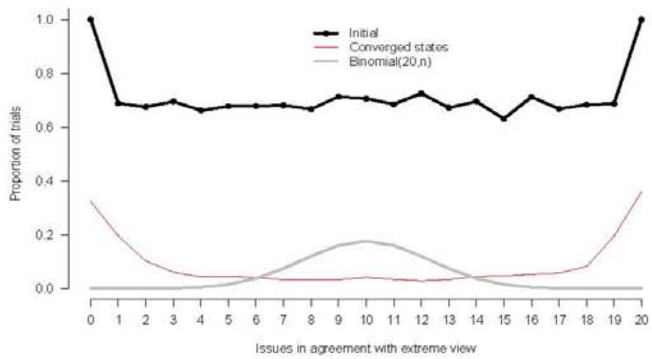

Fig. 5 Convergence distributions across across belief states for Simulation 1. Black line with filled points indicates mean number of initial states with specified agreement with extreme view (extremeness index). Thick grey line shows the distribution of possible knowledge states. Thin U-shaped line indicates proportion of simulations that converged to given extremeness index.

This simulation illustrates that the use of a knowledge space can produce the same basic phenomenon that the bounded influence conjecture is typically used to produce: multiple groups that tend to be at opposite ends of the belief spectrum. This happens despite lacking the bounded influence conjecture: agents are willing to interact with any other agent regardless of belief, yet the system does not converge to a single knowledge state.

The knowledge-space account produces these results for several reasons. First, two agents with extremely different influence one another only rarely, because the discussion must result in moving one agent from their current state to another legal states, which constitute only $15/1,048,576 = 0.0014\%$ of the possible states. This creates a gulf between most knowledge states (even intermediate ones) that is hard to overcome, because only the proper message can move one agent to a logically-consistent state. Furthermore, clustering in the extremes is encouraged because of the substantial oversampling of extreme states, which are necessarily close to one another, and thus have a chance of moving opinion of an agent.

Overall, Simulation 1 illustrates the basic premise that knowledge states, restricted because of a need for consistency between concepts, can indeed produce the same type of convergence phenomena that the bounded influence conjecture does. It also produces group polarization by default, with no additional assumptions. These results raise two questions, which will be explored in Simulations 2 and 3. First, do the convergence properties depend on the knowledge space being highly polarized? This will be explored in Simulation 2. Second, would we still see group polarization if the starting distribution was not so broadly distributed across the belief spectrum in a (perhaps) unrealistic manner. This will be explored in Simulation 3.

2.2 Simulation 2: Convergence in random knowledge spaces.

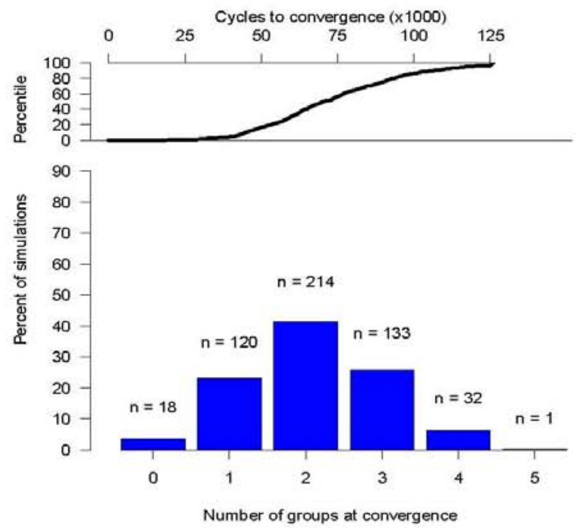

Fig. 6 Depiction of the convergence of 500 simulations in Simulation 2.

The first simulation showed how assumptions about the structure of knowledge, rather than the interaction rules of naive agents, can produce situations in which an interacting group can be influenced by any other agent's opinions but still converge to distinct belief groups, and not collapse to a single group. It also showed that despite the fact that the initial beliefs were distributed across the range of the belief space, the stable groups tended to converge to the extremes. This raises a couple related question: (1) will groups still tend to converge to extremes in knowledge spaces that do not oversample the tails of the distribution?; and (2) will agents still tend to converge to multiple groups in these situations, or will the collapse to a single group? The present simulation investigates this.

The basic steps in Simulation 2 were identical to Simulation 1, except that the initial distribution of states was chosen as follows: the two most extreme states were always included, but instead of choosing a value for p that ranged between 0 and 1 uniformly, p was chosen between .4 and .6. for each knowledge state. The parameter p was then used to sample each feature of a belief state. This convolution of a uniform and binomial distribution was used to expand the center region of the knowledge space, biasing it only slightly in the direction of the extreme views. A p uniformly chosen to be .5 would produce a space that is identical to an unvalenced space, where no dimensions have any real coherence with any underlying principle. Otherwise, the simulation was identical to Simulation 1.

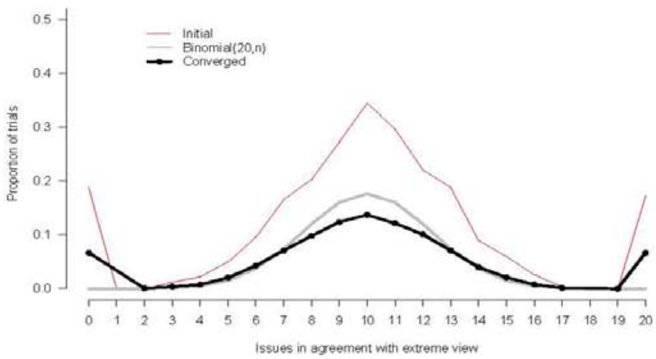

Fig. 7 Convergence distributions across across belief states for Simulation 2. Black line with filled points indicates mean number of initial states with specified agreement with extreme view (extremeness index). Thick grey line shows the distribution of possible knowledge states. Thin peaked (red) line indicates proportion of simulations that converged to given extremeness index.

Figure 6 shows the basic convergence properties of Simulation 2. Again, most simulations (all but 18) had converged by 125,000 cycles. Like Simulation 1, simulations converged to two states more often than others, but unlike Simulation 1, a considerable proportion of simulations converged to one and three states. This is interesting because without the heavy oversampling at the extremes, one might expect the simulations to tend to converge to a single state near the center of the extremity index, but this did not happen.

Figure 7 shows that the simulations do indeed tend to converge near the center of the belief space (thin peaked line). But they still tended to converge to *multiple states*. Convergence to moderate states occurs because, similar to Experiment 1, there is a large gulf between moderate states and the extreme states which often prevents agents from moving to the extremes. But convergence to multiple states is interesting, because one might assume that heavier sampling of moderate states would serve as an attractor that would encourage consensus.

The explanation for this outcome is that just because two states are equally moderate does not mean that they are similar. For example, consider the two following states:

$$11111111110000000000 \tag{1}$$

$$00000000001111111111 \tag{2}$$

Both might be considered moderate, yet they are in complete disagreement. In fact, each has more similarity to the two most extreme belief states (10/20 matches) than they do to one another (0/20 matches). Thus, is fairly easy for Simulation 2 to converge to multiple moderate belief states that still have gulfs between them wide enough to prevent convergence to a single state.

The combined results of Simulations 1 and 2 suggest that knowledge spaces can provide a powerful explanation for consensus formation and stable disagreement within an interacting community. Simulation 1 also produced a polarization effect that was not present in Simulation 2, whereby the belief a group converges to is more extreme than their average belief before convergence. Simulation 3 examines group polarization in more detail.

2.3 Simulation 3: Group polarization in consensus formation

Simulation 1 produced an unexpected result: not only did beliefs converge to multiple stable groups, the groups tended to stabilize at the extremes of the belief space. This result is akin to classic group polarization effects. However, this polarization might be somewhat of an artifact, because agents were initially spread broadly across the belief space, the convergence patterns might just appear extreme in comparison to the starting conditions. Traditionally, polarization effects can occur for a group that is already in general agreement, such that the consensus reached after discussion is still more extreme than the average of initial opinions.

Simulation 3 addresses this point by creating a belief space that is already highly polarized. In this simulation, rather than choosing the value p uniformly between 0 and 1 (as in Simulation 1) or uniformly between .4 and .6 (as in Simulation 2), p was chosen to be either .1 or .9 for each belief state. This configuration tended to converge to two stable states, so in this simulation, we ended each run whenever only two states remained. As before, the two most extreme states were always present in the knowledge space.

Figure 8 shows the outcome of this simulation. The critical comparison is between the thin black line (starting distribution) and the dashed line (ending distribution). As before, the simulations tended to converge to extreme states, and these states were in fact more extreme than the already polarized starting configurations. Each grey filled circle represent the number of agents holding a belief of one extremity index, across all simulations. The lowest thick U-shaped (red) line is the mean of these values across all simulations.

This simulation illustrates a novel account of the group polarization phenomenon. In the simulation, group polarization occurs because the more extreme views are the ones that are most central to the less extreme beliefs around it, in that they are closest to the most other states. Typically, movement between two less extreme belief states is less likely than movement to an extreme. Indeed, an agent can move to an extreme after interacting with another agent that may less extreme than the first agent, if it happens to adopt beliefs of the second agent that are more extreme. This differs fundamentally from many different accounts of group polarization because it does not assume the effect stems from social processes such as leadership or unwillingness to change opinion. Rather, polarization stems from the structure of the knowledge space. In these cases, the most extreme view is actually the most central view amongst extreme views, and so the easiest to agree upon. Less extreme views, which may represent more moderate beliefs that match the starting distribution better, are more difficult to converge upon because they tend to involve greater average belief change, even among initially moderate agents (who are simply moderate on different dimensions).

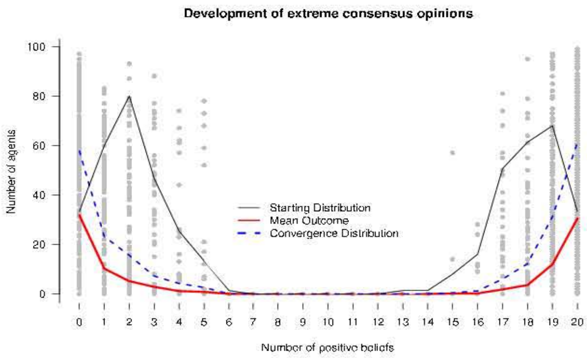

Fig. 8 Observed distribution showing group polarization. Thin black line shows average of initial distributions of belief states, which were binomially distributed with $p = .1$ or $p = .9$. Solid thick line shows the mean of all outcome distributions after convergence to two states, and the dashed line shows the proportion of trials that a particular state was converged to.

3 Discussion

Overall, these simulations illustrate an alternative approach to inducing group-level processes in social simulation. They rely on the notion of a knowledge space, which provides a richer representation through which to simulate belief transmission than unidimensional representations typically offer.

Figure 9 illustrates the basic differences between the knowledge spaces used in the three simulations. The top panel shows a single knowledge space sampled using the methods in Simulation 1. In it, there are a number of states near the extremes which tend to be close to one another (and thus enable easier movement between), with others distributed across the spectrum that tend to be fairly isolated. The center panel shows a knowledge space similar to Simulation 2, in which states tend to be nearer the center, yet they are also isolated from one another. The bottom panel shows knowledge spaces similar to Simulation 3, which are polarized to begin with, and so are all close to one another.

Whether the results here can apply to real-world organizations depends upon whether beliefs in those organizations can be reasonably approximated by a multi-dimensional binary knowledge space with valenced values with a

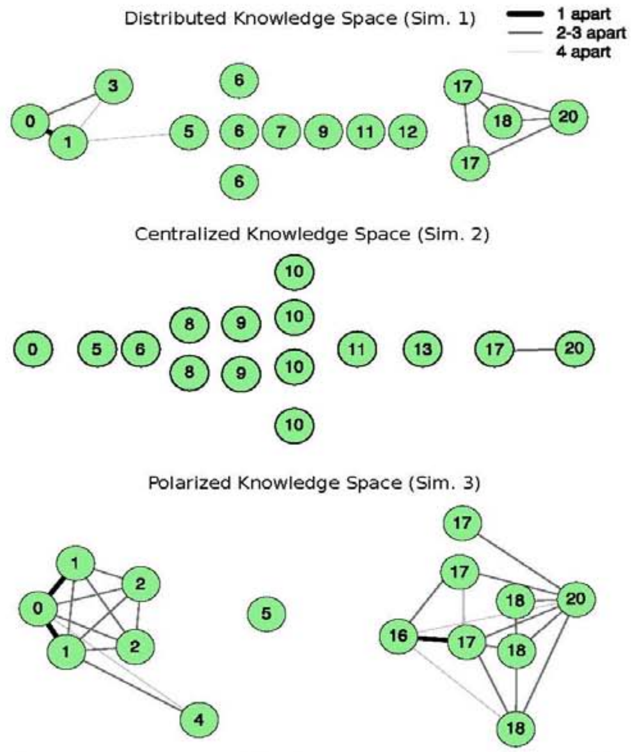

Fig. 9 Illustration of the closeness of different belief states for the three simulations. The thickness of the line shows how many features two states differ by. Unconnected states differ by more than 4 features.

limited number of intermediate states that can logically or customarily exist. Clearly, this would not be true for some classes of beliefs in arbitrary groups of people. A general broad-based opinion survey about consumer products might have essentially arbitrary valences about unrelated topics, and so would produce a space more akin to Simulation 2. But other domains may be more relevant. For example, Butts and Hilgeman (2003) showed an example in the domain of religous beliefs that fit this description well, and identified an empirical knowledge space that both had an overall valence (in terms of religiousness) and individual intermediate states that were logically or theistically coherent.

Another example comes from work using statistical methods to identify groups within a population (Mueller & Veinott, 2008). They examined the 2006 U.S. Senate votes on 19 issues identified by the AFL-CIO as important for labor union interests. Not surprisingly, beliefs clustered at the extremes, with Democrats largely in support of union issues and Republicans largely opposing union issues. However, there was quite substantial divergence from the "most extreme" ends of the scale. The same data can be examined in terms of their distribution across a knowledge space, as shown in Figure 10.

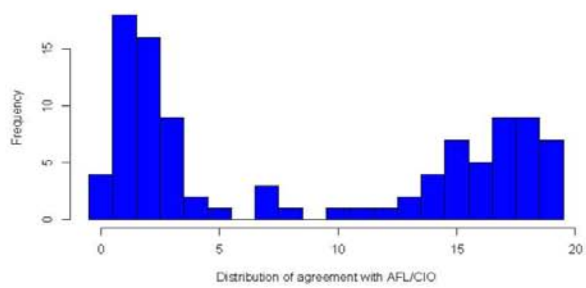

Fig. 10 Senate voting distribution on 19 issues identified by the AFL-CIO as important for union interests. Horizontal axis indicates number of issues in agreement with the union.

The senate voting shows a fairly polarized set of beliefs, but with substantial deviations from the most extreme views in both directions. Yet it illustrates that there do indeed exist the types of polarized belief spaces simulated in Simulation 3. The degree of polarization is remarkable yet probably not unexpected. The present simulations might expect even greater polarization and tighter consensus groups, but Senators may be also be highly influenced by opinions outside of the Senate body, which may drive some individuals away from the typical positions.

Nevertheless, the simulation approach described here has offered a clear alternative to the standard bounded influence conjecture. In addition, it offers the possibility of representing more complex knowledge structures, and making close contact to data that can be obtained using surveys and other similar methodologies. It also provides a single account of opinion dynamics and group polarization, and indeed its account of group polarization is novel.

Table 1 Comparison of the assumptions of bounded influence models and the knowledge-space model.

Bounded influence models	*Knowledge-space model*
Beliefs are represented as a single continuous-value variable	Beliefs are represented as a multidimensional binary simplex
Any intermediate belief between two extremes is feasible	Many or most potential intermediate belief states are impossible
Belief change happens incrementally, moving in a fairly smooth trajectory between two extremes	Belief change is saltatory, jumping among a fairly small set of possible states
Agents are unwilling to engage with those with alternate opinions, even moderate ones	Agents will interact with others regardless of their beliefs
No direct account of group polarization	Group polarization arises because of the structure of the knowledge space

3.1 Testing the Bounded Influence conjecture

It is important to recognize that these simulations do not show that the bounded influence conjecture completely wrong, or that alternative account of the group polarization phenomenon are incorrect. It simply provides an alternative theory that can be tested empirically. Identifying critical differences between these theories and testing them may also be useful because it can help clarify what the central assumptions of each approach really are. Furthermore, there are a number of assumptions outside the scope of the models that can account for some of these effects. Notions of social network, geographical distance, and group membership may greatly constrain both models. As sort of a thought experiment, several of the tacit assumptions of the bounded influence approach are compared to the knowledge space approach in the following table. These assumptions constitute distinct differences between the two approaches that could lead to testable hypotheses that may discriminate between the two theories using behavioral experimentation.

Overall, these simulations challenge one common approach in understanding belief transmission through an organization. Much previous theorizing has assumed that a divergence of belief itself prevents agents from interacting. This bounded influence assumption arose in part because of the impoverished representations typically used by these models. By expanding the notion of belief to a multivariate complex, and restricting the legal states within the resulting space, the present models can produce convergence to multiple groups almost by default, and also produce group polarization with no further assumptions. Future work in opinion dynamics should take more seriously cognitive aspects of belief, and look to cognitive theory, in contrast to physical systems, for inspiration and guidance.

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APPENDIX D: Collection of News Headlines Illustrating Divergent Models of Cultural Ideas

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